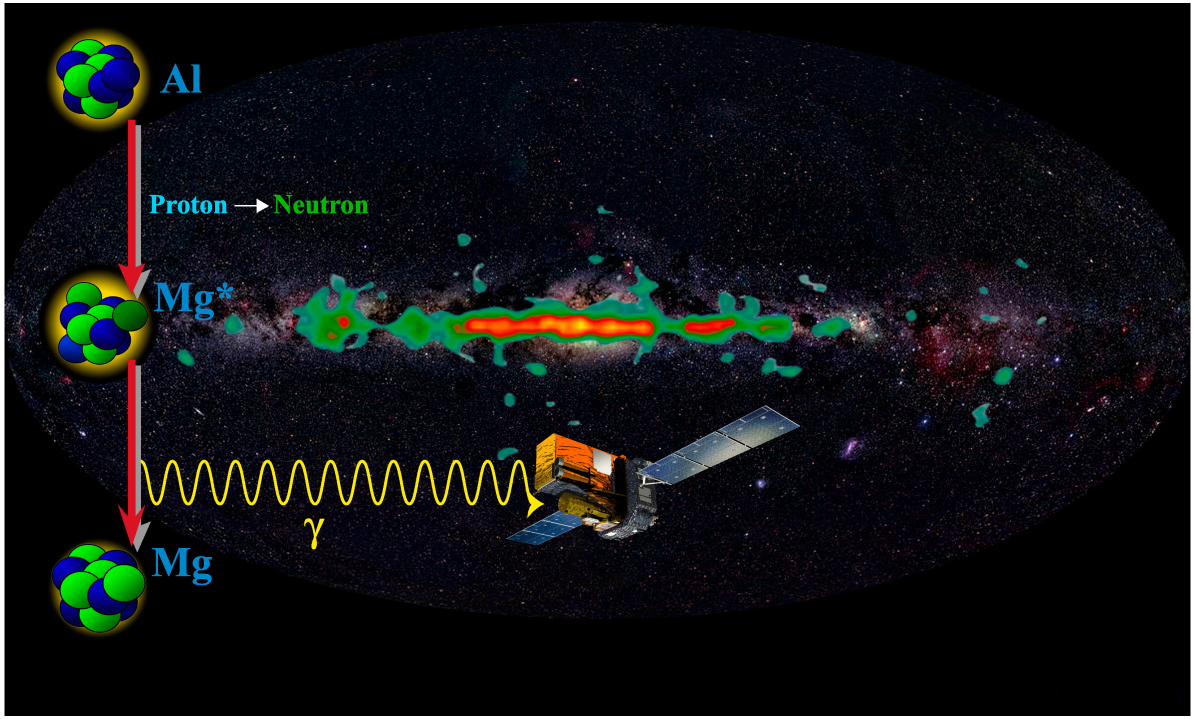
Gamma-Ray Line Measurements from SNe



Roland Diehl

(MPE Garching, Germany)
with
Martin Krause, Thomas Siegert, Jochen Greiner, Xiaoling Zhang (MPE),
Wolfgang Hillebrandt, Keiichi Maeda, and many others at other institutions

Gamma-Ray Lines and their Messages

- Radioactive Trace Isotopes are Nucleosynthesis By-Products

Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	^{7}Be → ^{7}Li*	478
^{56}Ni	111 d	^{56}Ni → ^{56}Co* → ^{56}Fe*+e^{+}	158, 812; 847, 1238
^{57}Ni	390 d	^{57}Co→ ^{57}Fe*	122
^{22}Na	3.8 y	^{22}Na → ^{22}Ne* + e^{+}	1275
^{44}Ti	85 y	^{44}Ti→^{44}Sc*→^{44}Ca*+e^{+}	78, 68; 1157
^{26}Al	1.04 10^{6}y	^{26}Al → ^{26}Mg* + e^{+}	1809
^{60}Fe	3.8 10^{6}y	^{60}Fe → ^{60}Co* → ^{60}Ni*	59, 1173, 1332
e^{+}	…. 10^{5}y	e^{+}+e^{-} → Ps → γγ..	511, <511

SNe

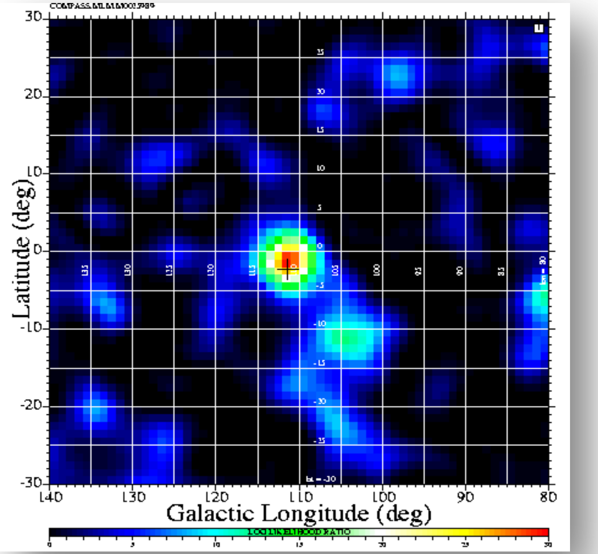
individual object/event

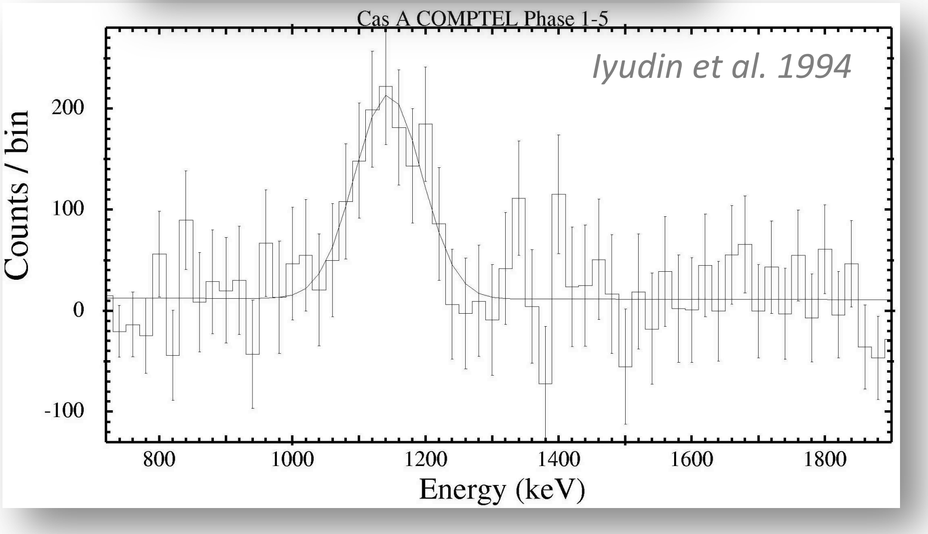
cumulative from many events

- For Gamma-ray Spectroscopy We Need:
  - Decay Time > Source Dilution Time (→ no < days lifetimes)
  - Yields > Instrumental Sensitivities (→ no elements > Fe)

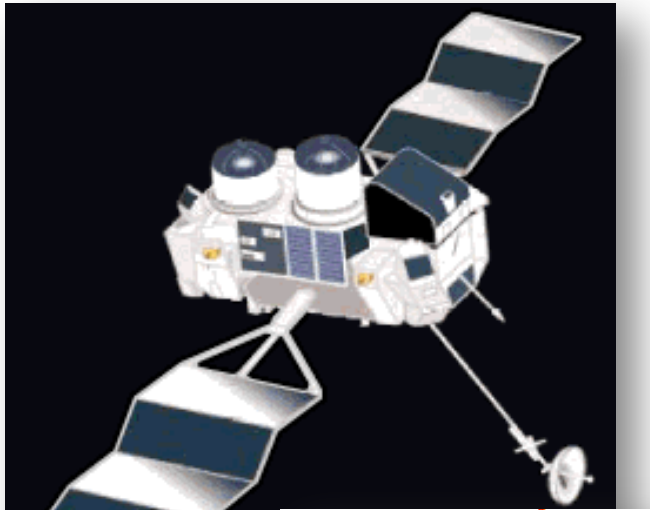
Discovery of ^{44}Ti from Cas A

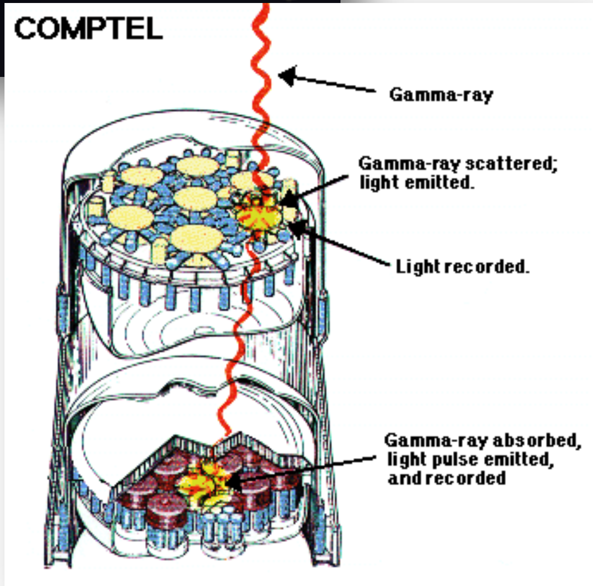
- COMPTEL on the Compton Gamma Ray Observatory



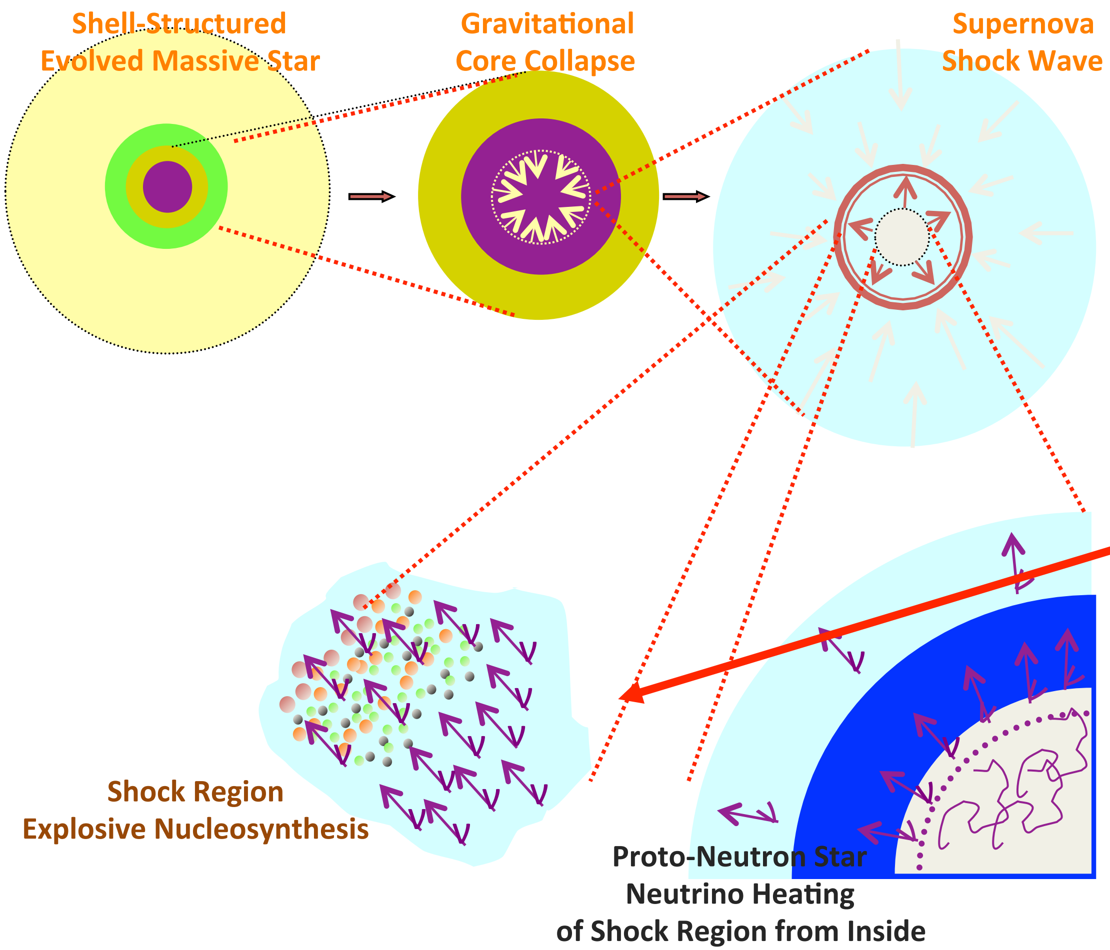


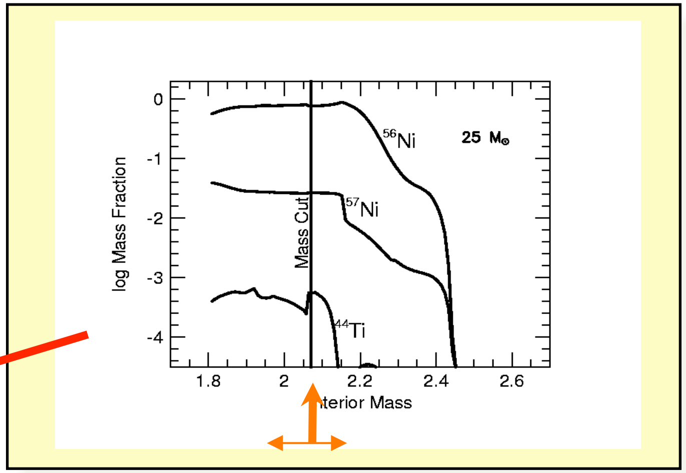
Iyudin et al. 1994

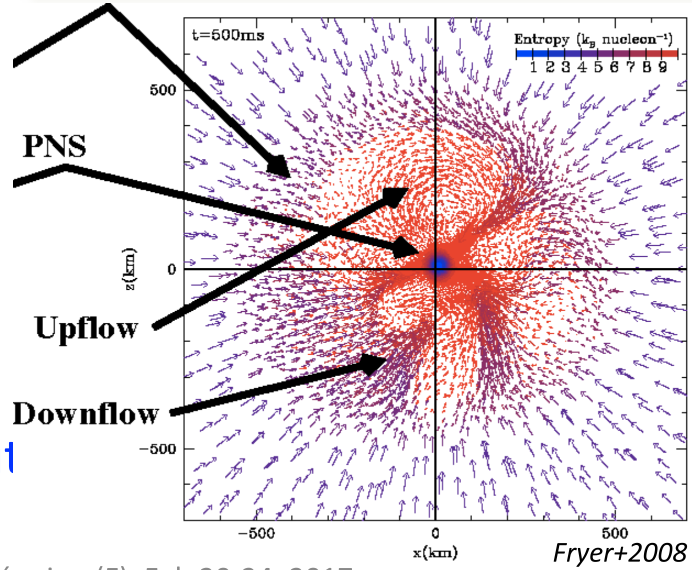




Nucleosynthesis in CC-Supernova Models and ^{44}Ti







Fryer+2008

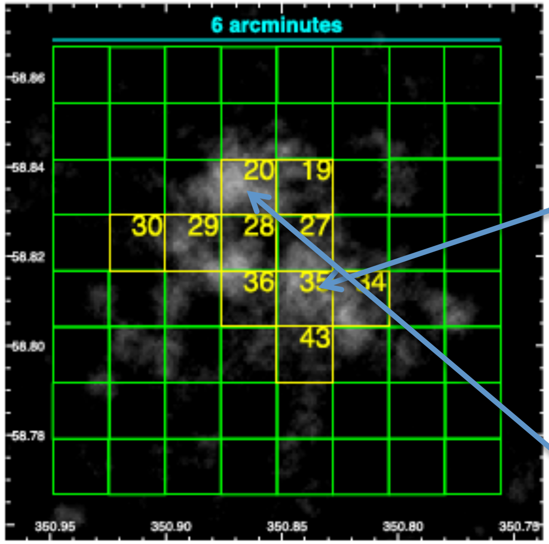
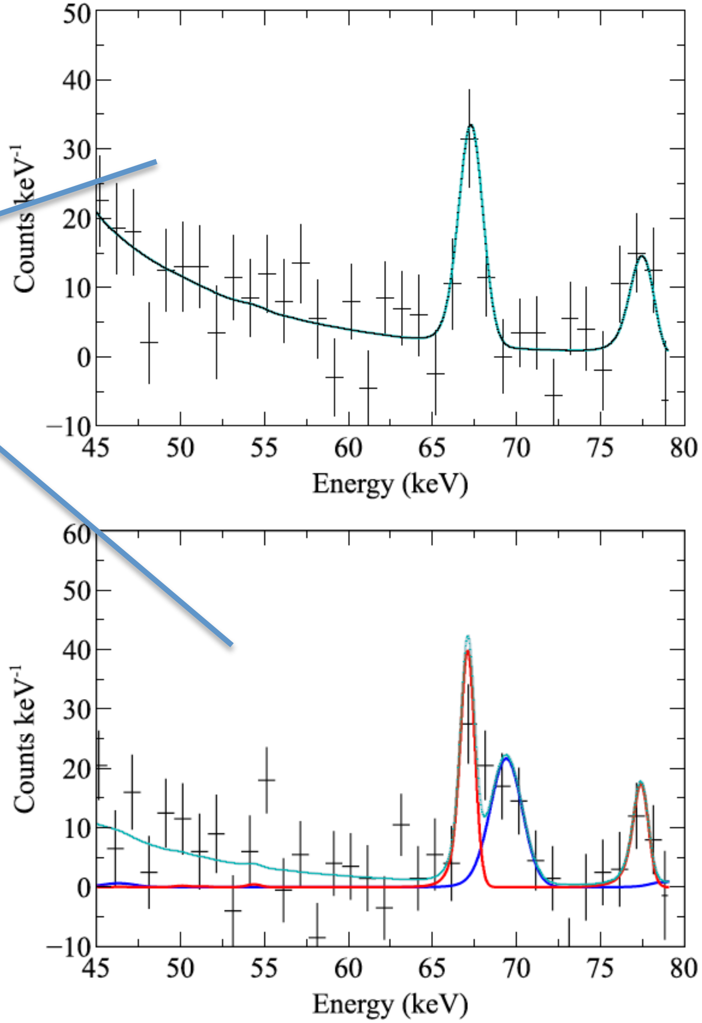
- ^{44}Ti Produced at $r < 10^3$ km from α-rich Freeze-Out

  => Unique Probe (+Ni Isotopes)

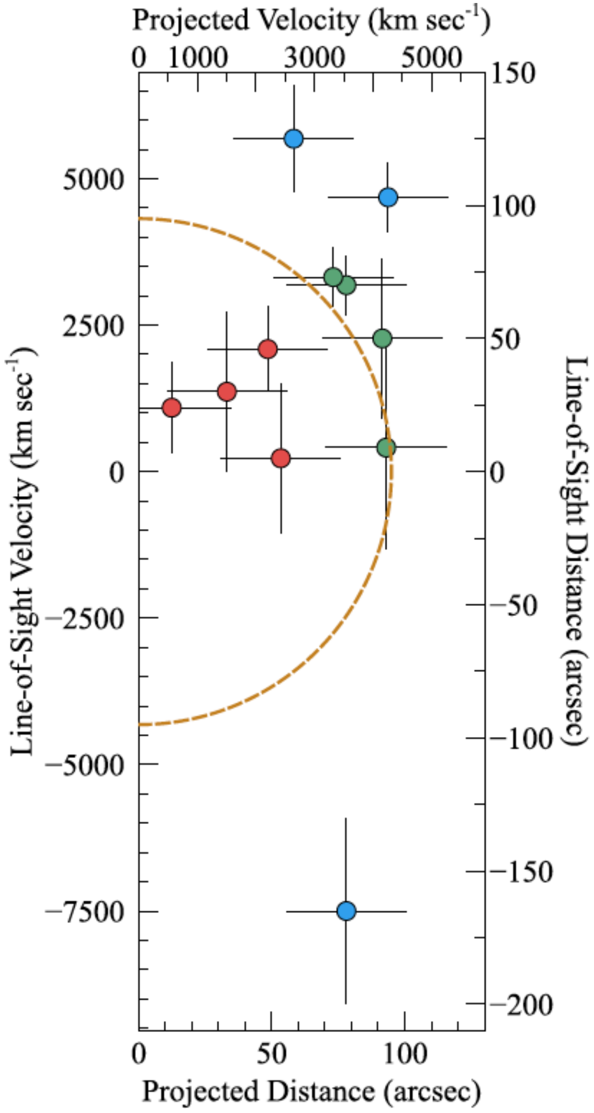
NuSTAR update: ^{44}Ti in Cas A

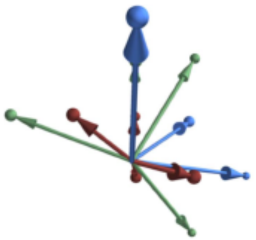
2.4 Msec NuSTAR campaign
Grefenstette et al. 2017

– Imaging resolution allows to spatially resolve Cas A's ^{44}Ti:

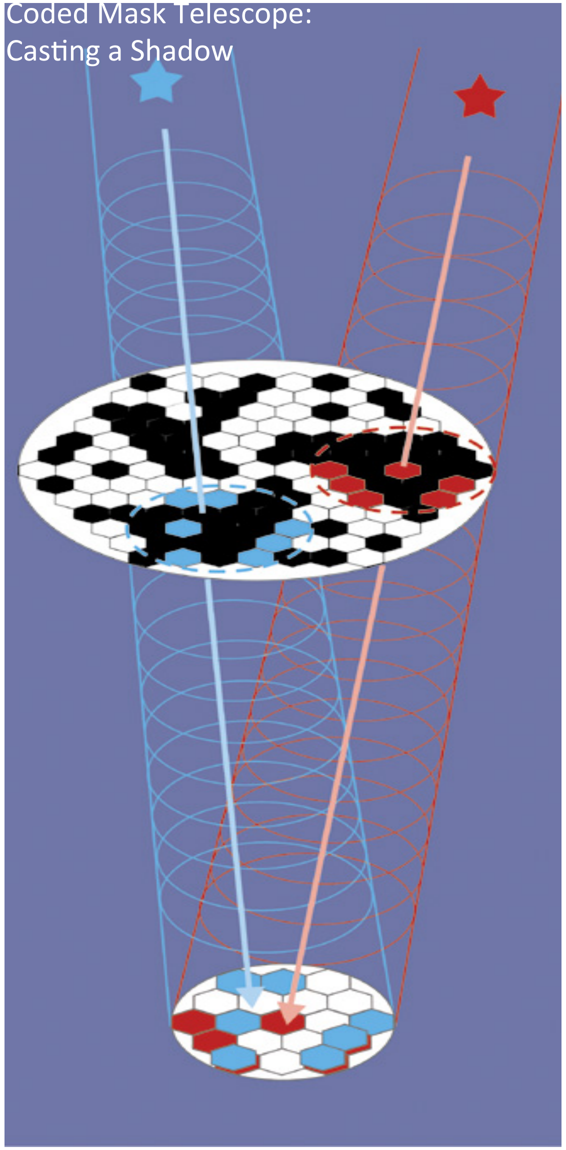



→ motion away
from us,
and in clumps





The SPI Ge γ-ray Spectrometer on INTEGRAL



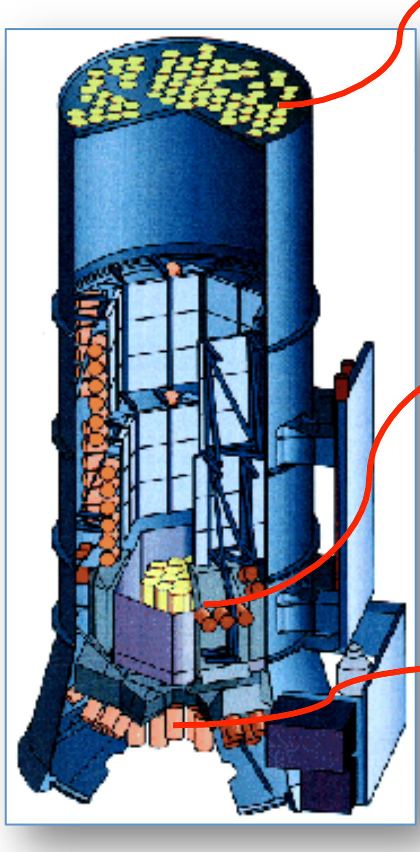
Coded-Mask Telescope

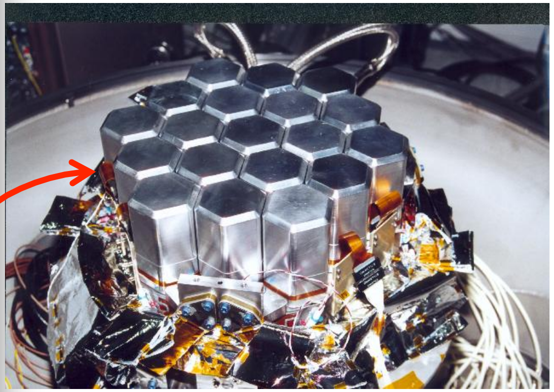
Energy Range 15-8000 keV

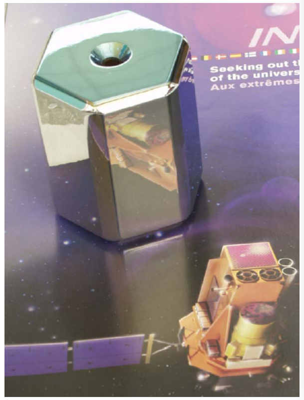
Energy Resolution ~2.2 keV @ 662 keV

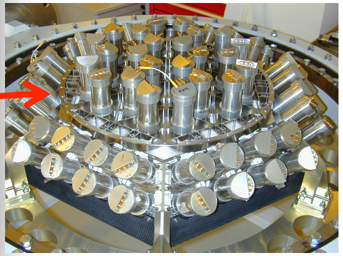
Spatial Precision 2.6° / ~2 arcmin

Field-of-View 16x16°



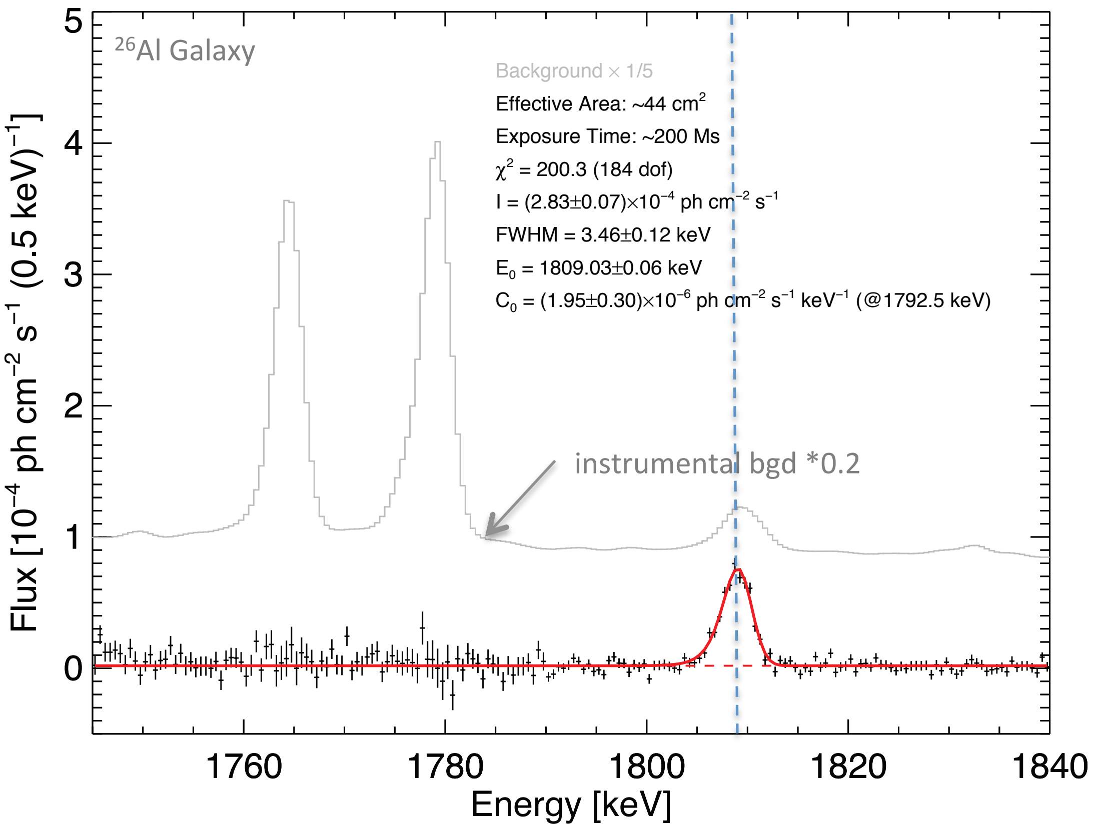






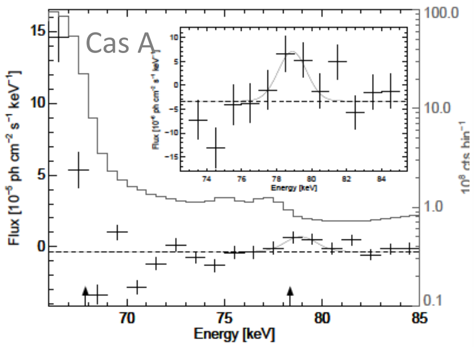
Gamma ray spectroscopy with SPI: instrumental lines

- it works:
  - ^{26}Al line 1808.6 keV
  - instrumental lines
    - 1810 keV
    - 1779 keV
    - 1764 keV
  - ...also: SN ^{56}Ni, ^{44}Ti

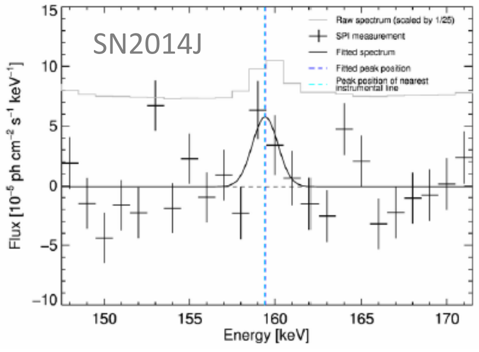


^{26}Al Galaxy

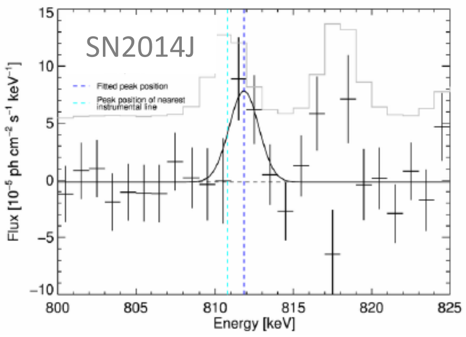
instrumental bgd *0.2



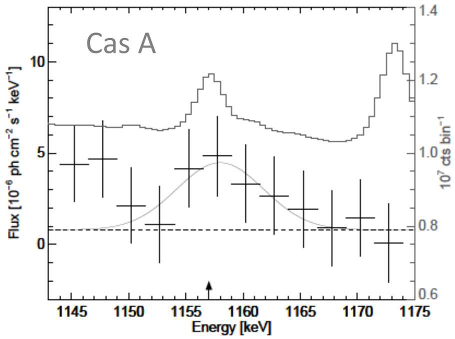
Cas A



SN2014J

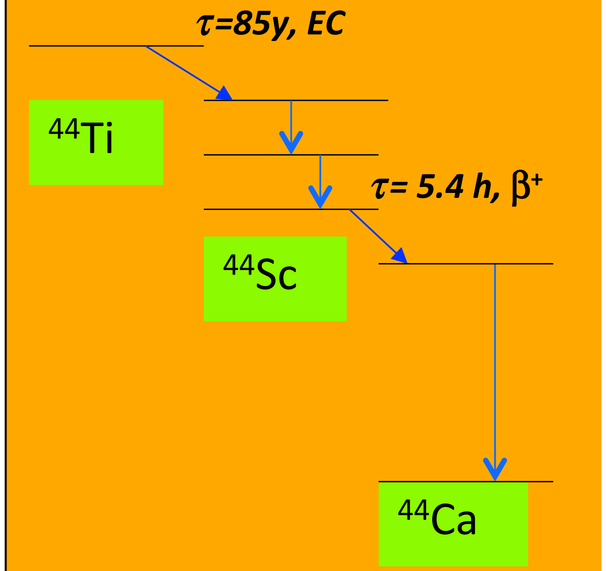


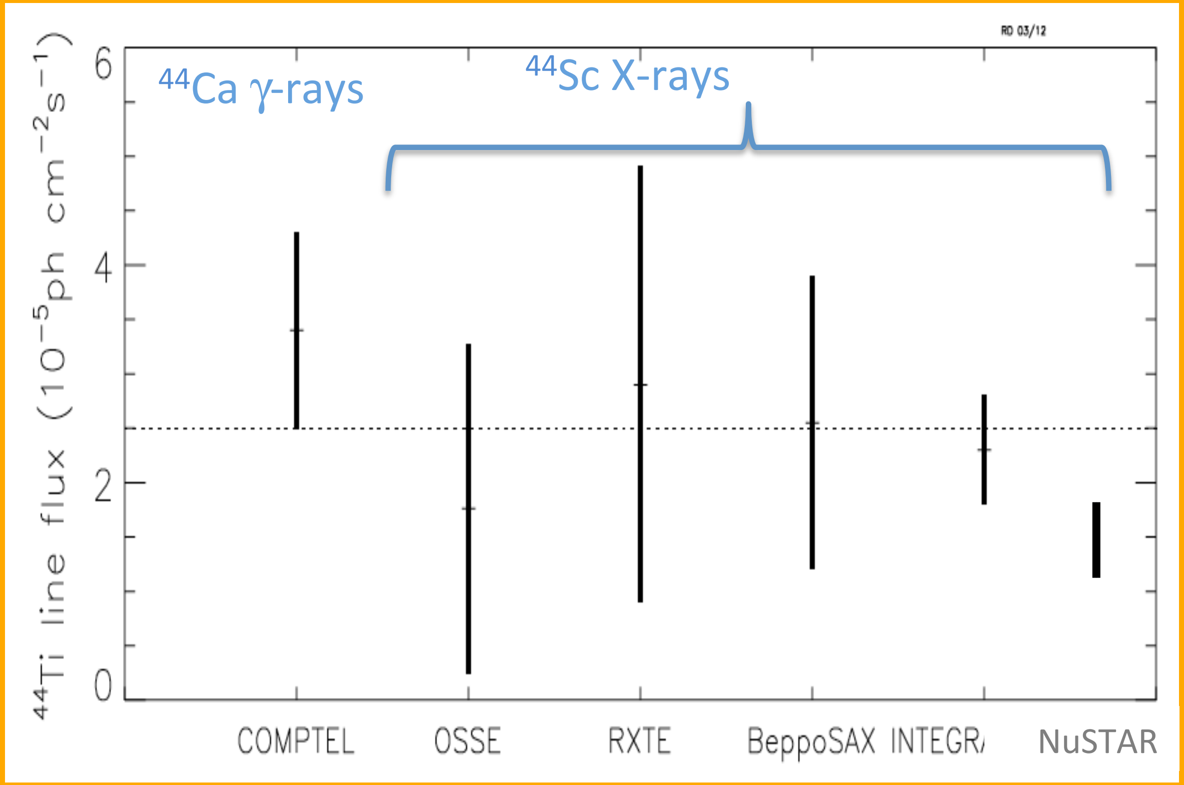
SN2014J



Cas A

^{44}Ti γ-rays from Cas A





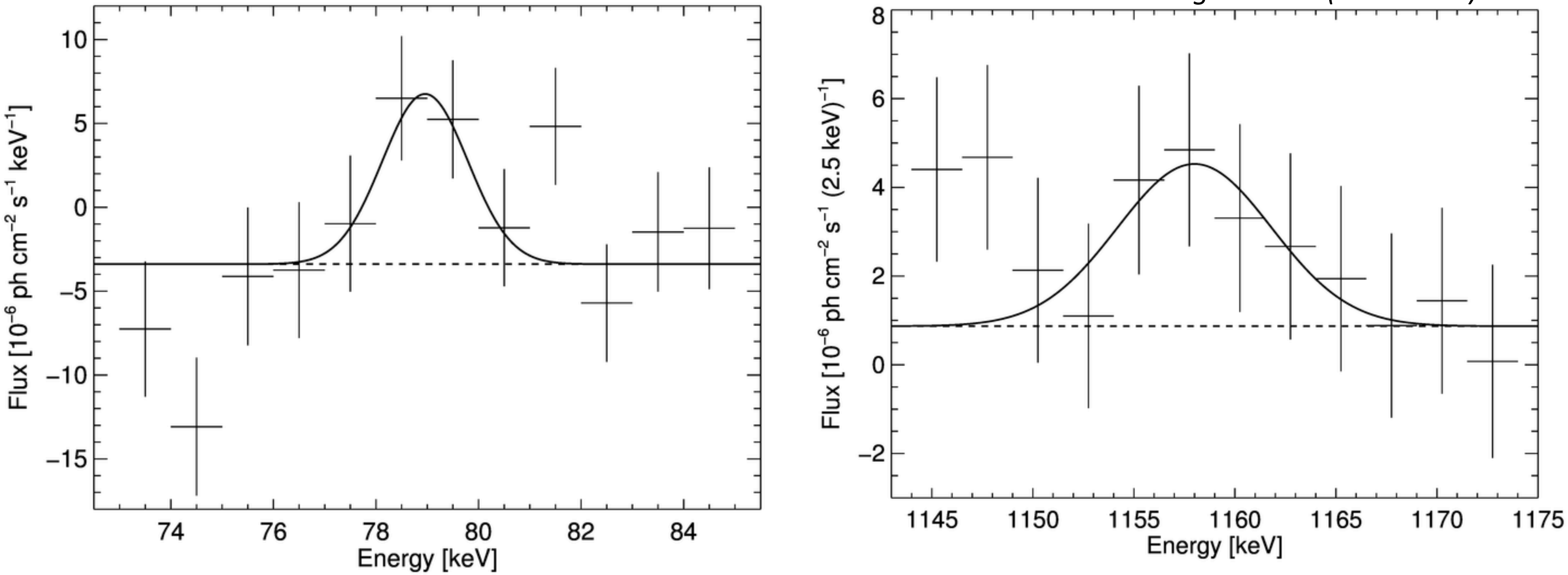
↳ ^{44}Ti Ejected Mass ~1.23 ±0.25 10^{-4} $M_\odot$

SPI Re-Analysis of Cas A for ^{44}Ti

Using cumulative data from >12 years,
and a new instrumental-background treatment

→ We see the 78 keV and 1157 keV line emission

Siegert et al. (A&A 2015)

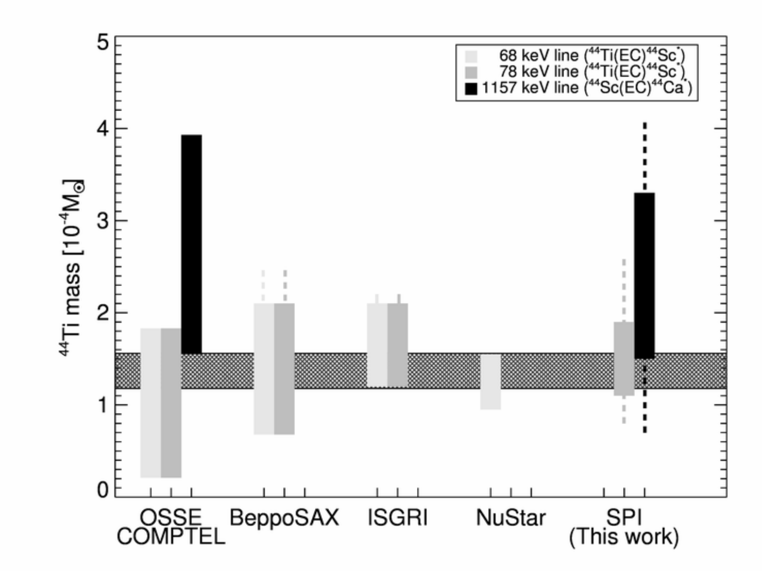


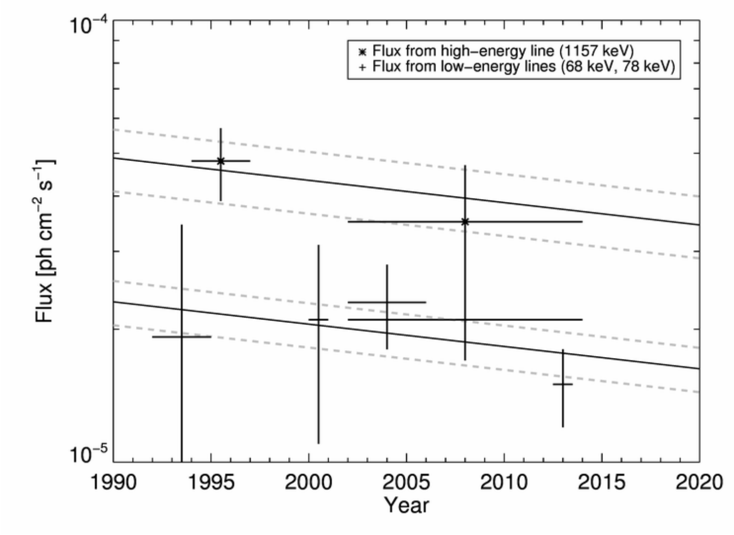
– Doppler broadening: 4300±1600 / 2200±1600 km s^{-1} (78, 1157 keV)

^{44}Ti from Cas A

- Consolidated Mass Determination:
  - Different instruments & lines combined

Siegert et al. 2015



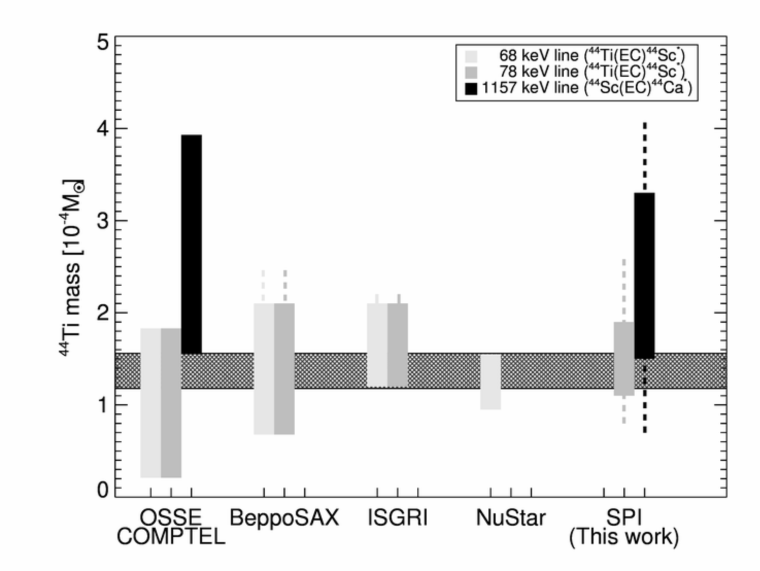


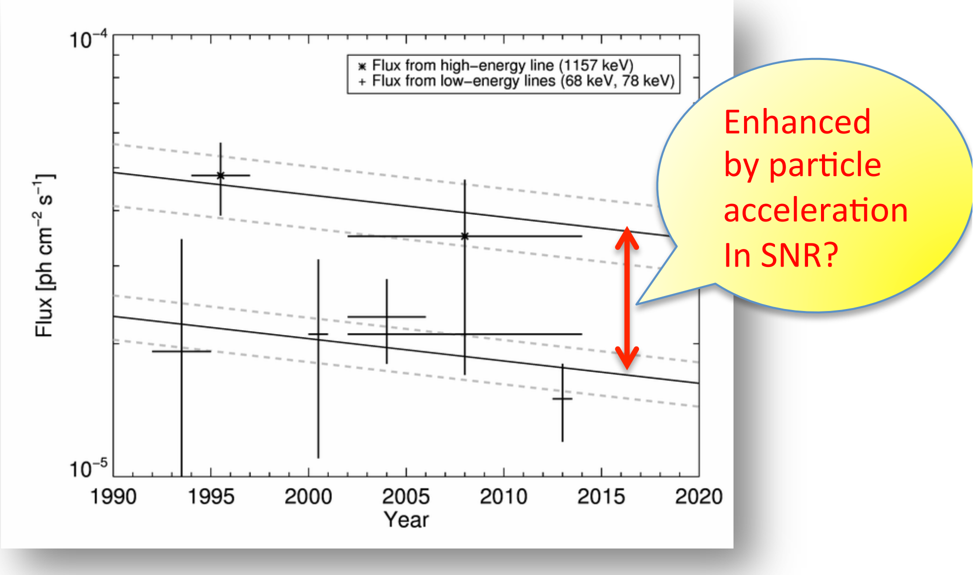
- ^{44}Ti mass = (1.37 ± 0.19) 10^{-4} M$_\odot$ (all measurements)
- ^{44}Ti mass = (1.29 ± 0.15) 10^{-4} M$_\odot$ (78 keV line only)
- ^{44}Ti mass = (2.72 ± 0.43) 10^{-4} M$_\odot$ (1.157 MeV line only)

^{44}Ti from Cas A

- Consolidated Mass Determination:
  - Different instruments & lines combined

Siegert et al. 2015





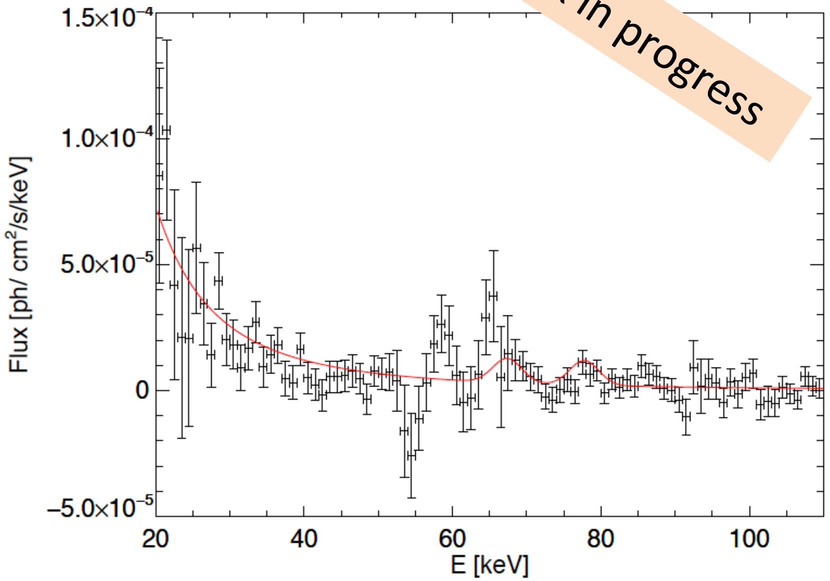
Enhanced by particle acceleration In SNR?

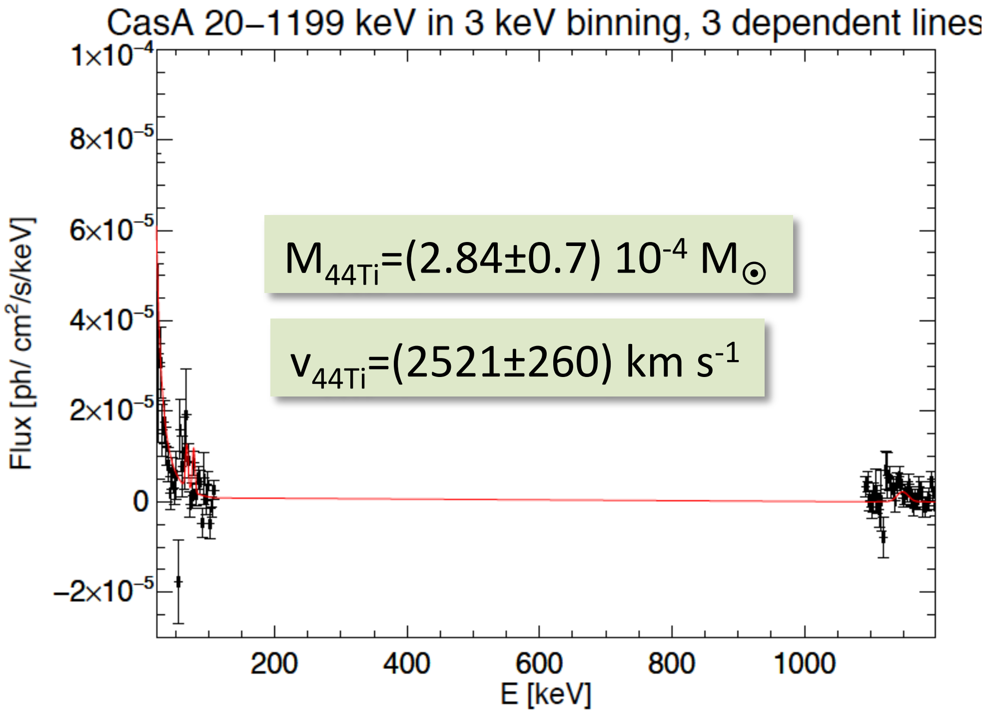
- ^{44}Ti mass = $(1.37 \pm 0.19)\ 10^{-4}\ M_\odot$ (all measurements)
- ^{44}Ti mass = $(1.29 \pm 0.15)\ 10^{-4}\ M_\odot$ (78 keV line only)
- ^{44}Ti mass = $(2.72 \pm 0.43)\ 10^{-4}\ M_\odot$ (1.157 MeV line only)

Update: 3-line analysis

work in progress

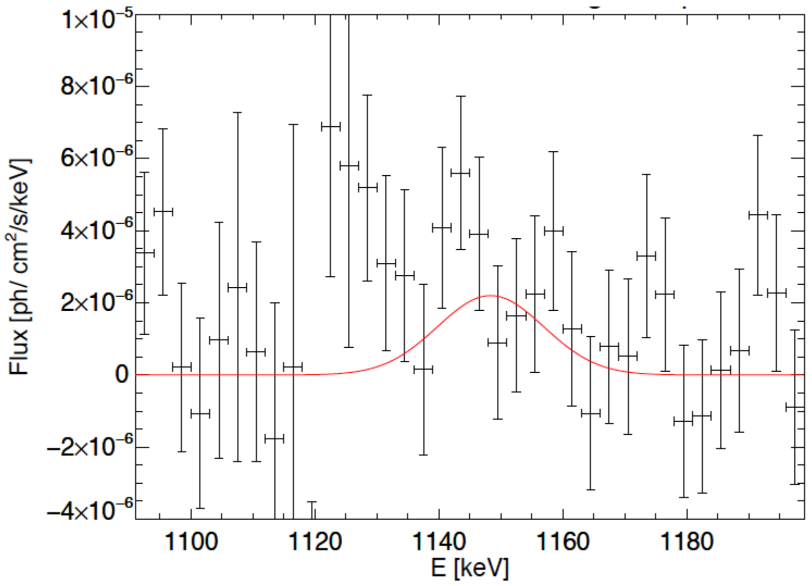
- INTEGRAL Deep Exposure Program 2016-2017
  - » additionally 2 Msec of Cas A & Tycho region; currently: ~8.6 Ms
- Refined analysis (Weinberger+, preliminary)
  - » use templates for blended-lines background features
  - » constrain ^{44}Ti through 3-line set (one line amplitude + cont fitted)



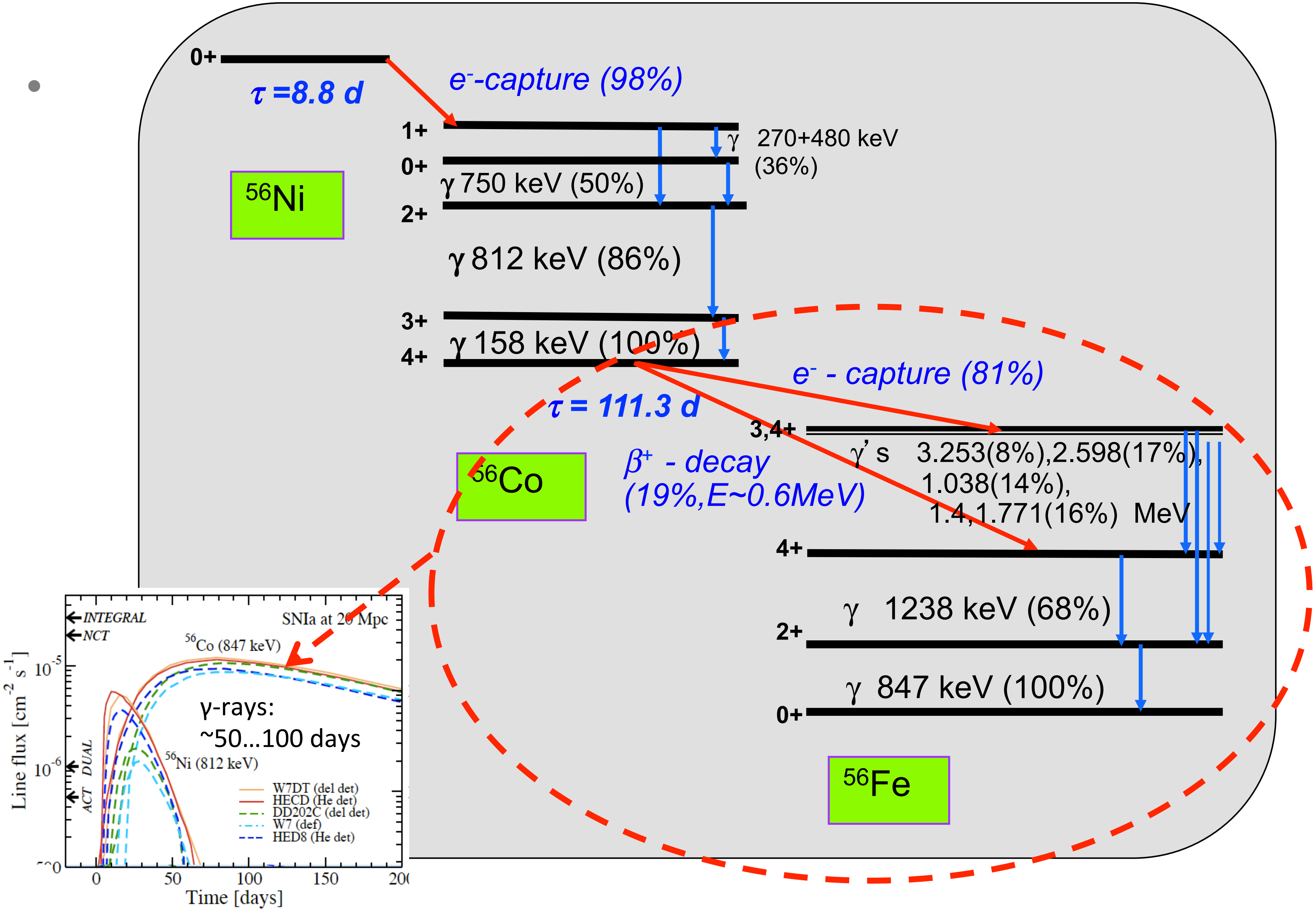

CasA 20–1199 keV in 3 keV binning, 3 dependent lines

M_{44Ti}=(2.84±0.7) 10^{-4} $M_\odot$

v_{44Ti}=(2521±260) km s^{-1}

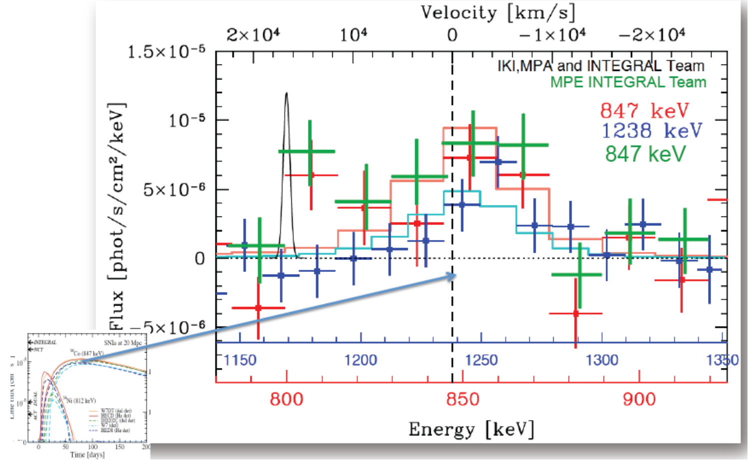


^{56}Ni radioactivity: Decay chain, γ rays, e^+



SN2014J data Jan – Jun 2014: ^{56}Co lines

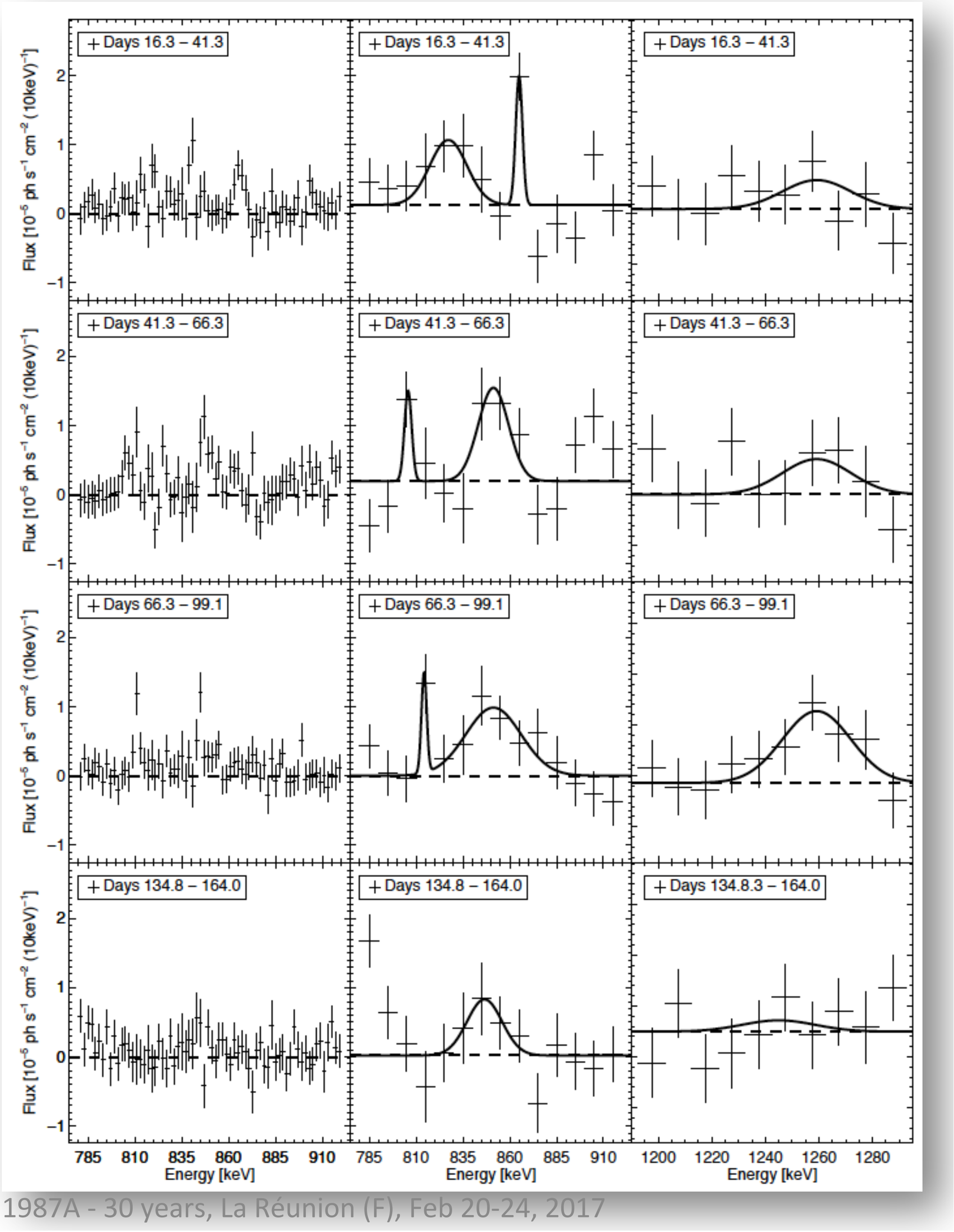
- Doppler broadened ✓



- Split into 4 time bins
- Coarse & fine spectral binning

→ Observe a structured and evolving spectrum

- expected:
  gradual appearance
  of broadened ^{56}Co lines
  - *Diehl et al., A&A (2015)*

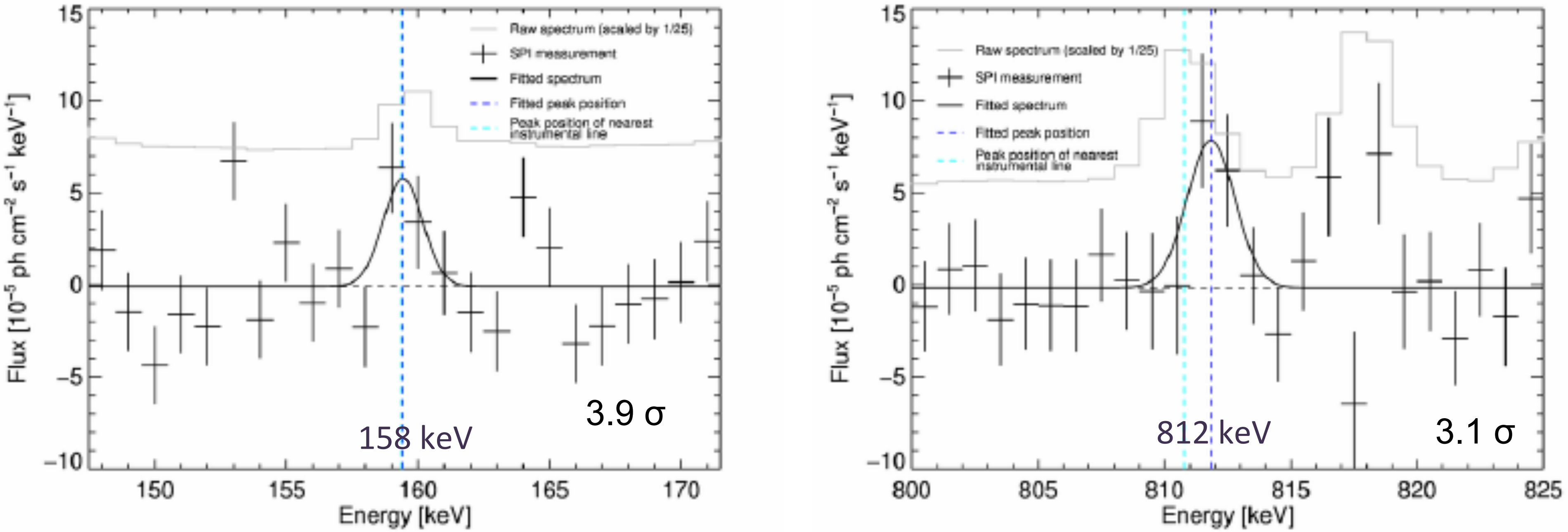


SN2014J: Early ^{56}Ni (τ~8.8d)

Spectra from the SN at ~20 days after explosion

- Clear detections of the two strongest lines expected from ^{56}Ni

Diehl et al., Science (2014)



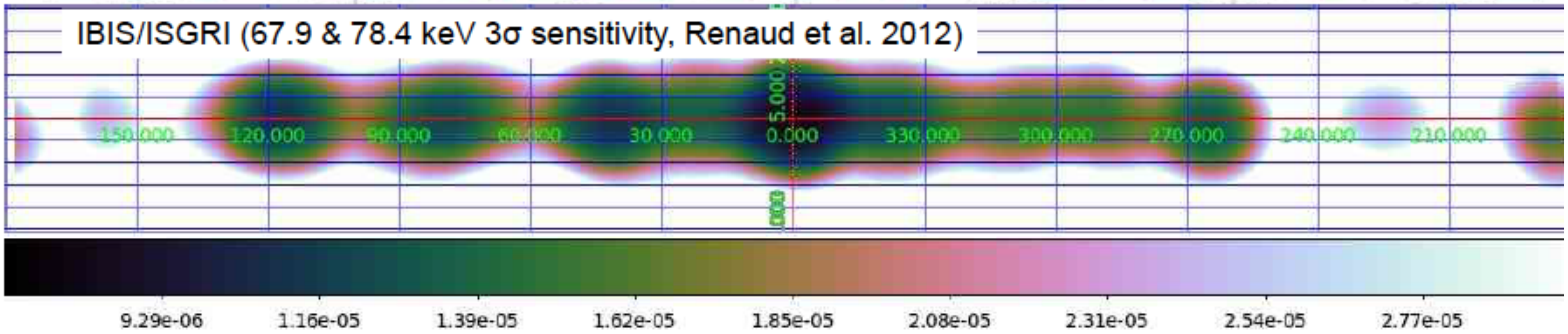
- Intensities:
  (1.14 ±0.43) 10^{-4} ph cm^{-2} s^{-1} (158 keV line)
  and (1.91 ±0.67) 10^{-4} ph cm^{-2} s^{-1} (812 keV line)
- Corresponding ^{56}Ni mass (backscaled to explosion): ~0.06 $M_\odot$

- Aspects from the population of supernovae

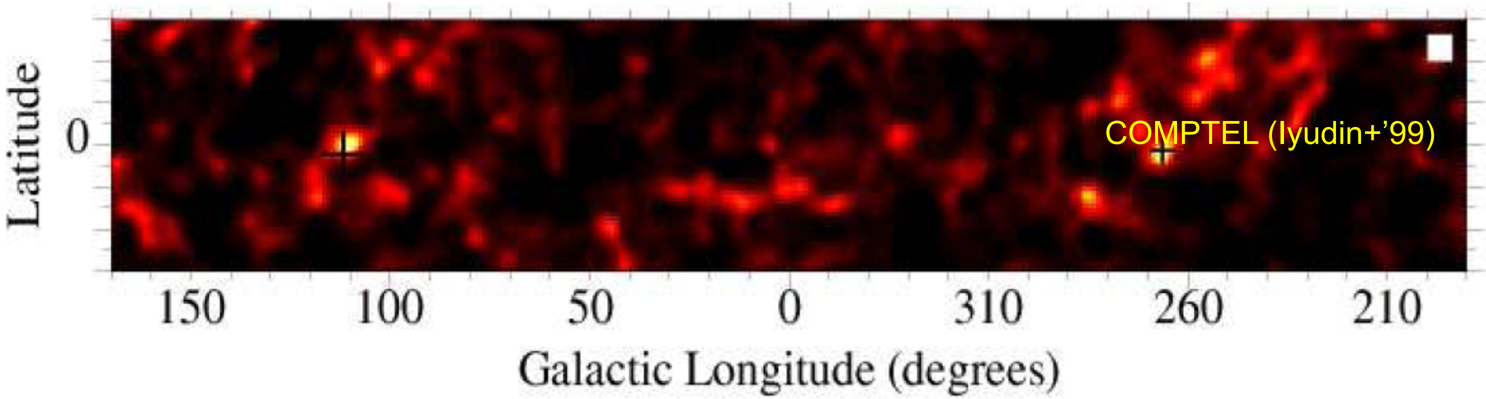
Survey: Are all Core Collapse Supernovae ^{44}Ti Sources?

- Cas A is the ONLY Source Seen in our Galaxy
- Sky Regions with Most Massive Stars (inner Galaxy) are ^{44}Ti Source-Free
- We would expect to see > a few of such sources!

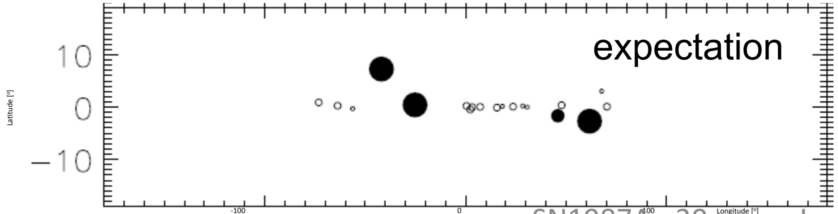
see also Tsygankov+2016



IBIS/ISGRI (67.9 & 78.4 keV 3σ sensitivity, Renaud et al. 2012)



COMPTEL (Iyudin+'99)

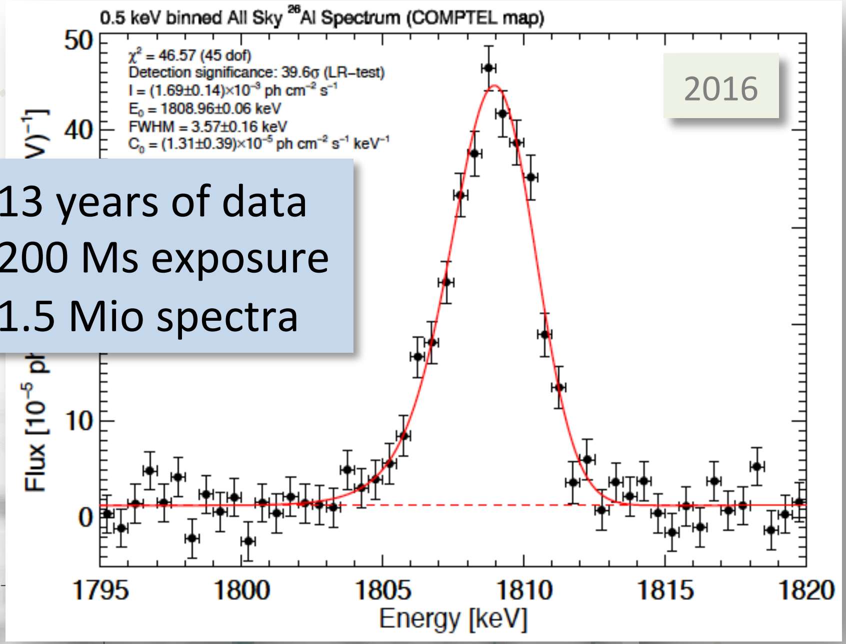


expectation

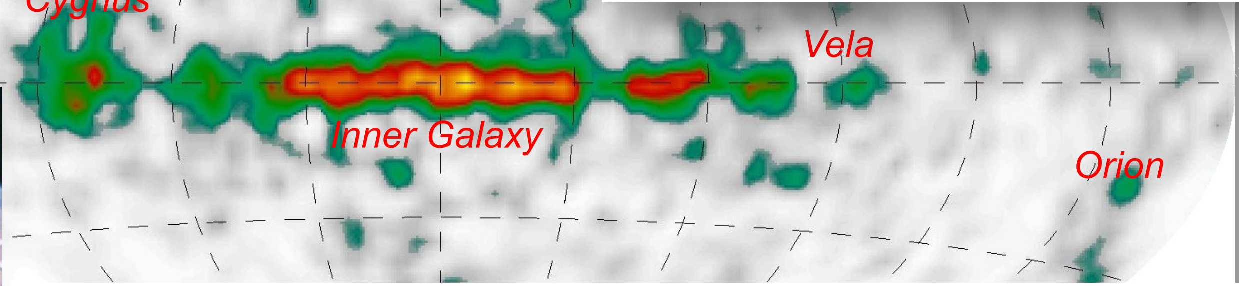
The et al. 2006; *see also Dufour & Kaspi 2013*

^{26}Al in our Galaxy: γ-ray Image and Spectrum


SPI on INTEGRAL: 2002-...(2029)



>13 years of data
>200 Ms exposure
>1.5 Mio spectra




COMPTEL on CGRO
1991-2000

Nucleosynthesis from Massive-Star Groups in the Current Galaxy:

Current Enrichment (~My) from ^{26}Al γ-rays

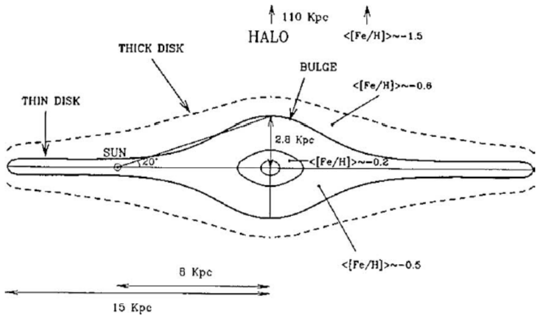
Using the ^{26}Al Line to Characterize the Galaxy’s SN Activity

→ Diehl et al., Nature 2006
*→ Diehl et al., A&A 2010**
*→ Diehl et al., in prep. (2017)**

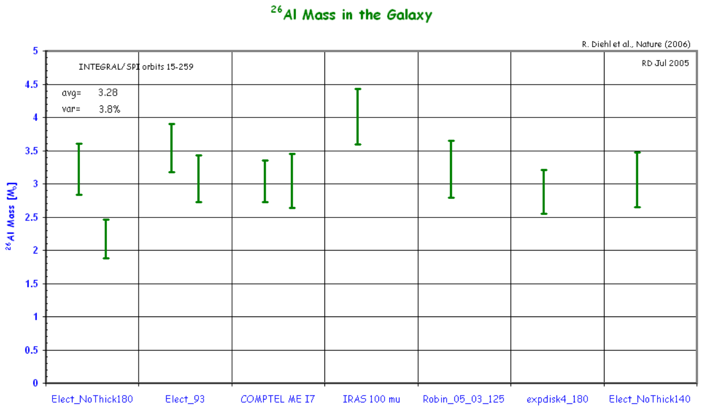
Measured Gamma-Ray Flux*

**) better account for foreground emission*

Galaxy Geometry

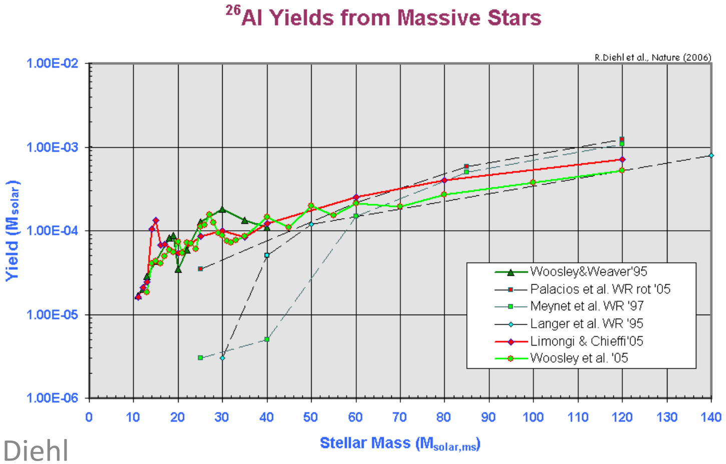


- ^{26}Al Mass in Galaxy = 2.0 (±0.3) $M_\odot$

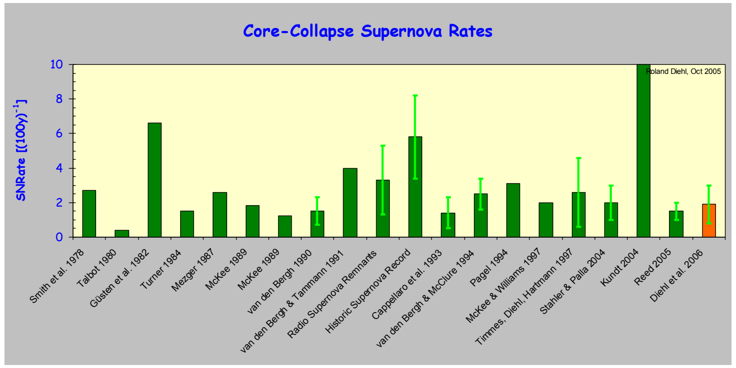


Stellar Mass Distribution,

^{26}Al Yields per Star



- ✓ cc-SN Rate = 1.3 (± 0.4) per Century

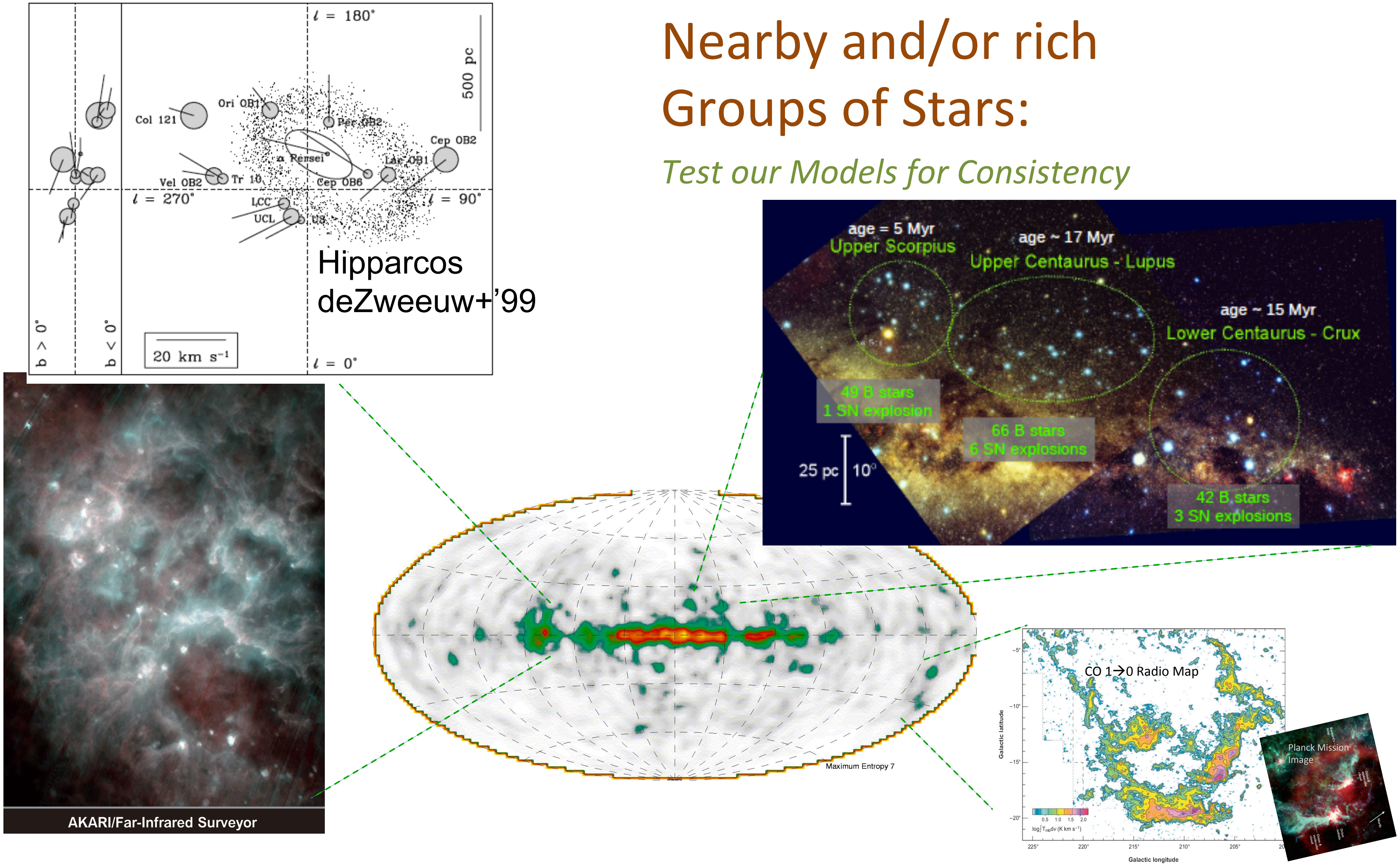


- ✓ Star Formation Rate = 2.8 $M_\odot$/yr

Resolving ^{26}Al Emission from Specific Groups of Stars

Nearby and/or rich Groups of Stars:

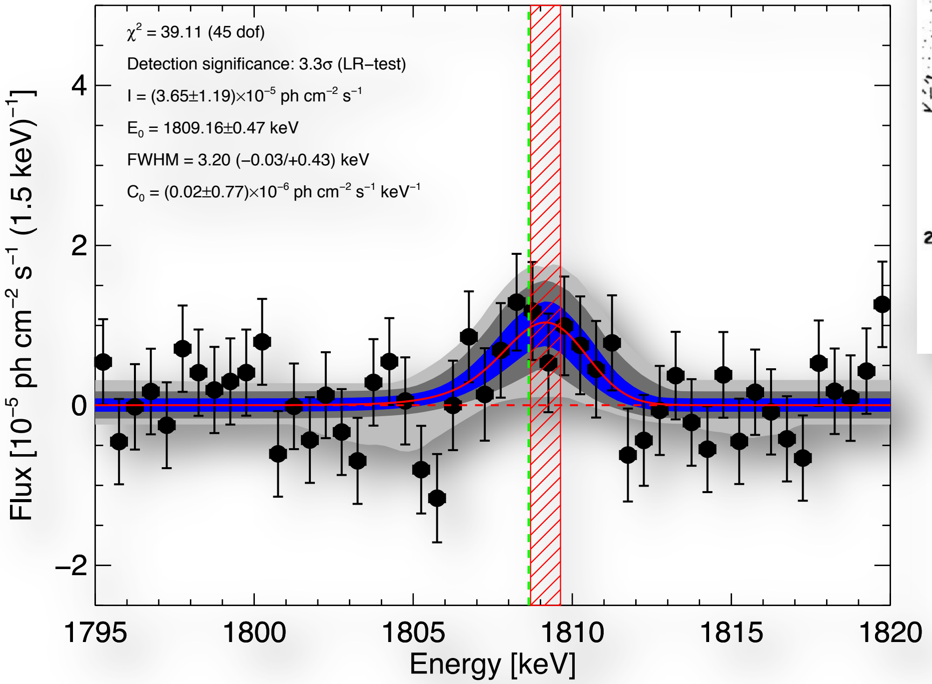
Test our Models for Consistency

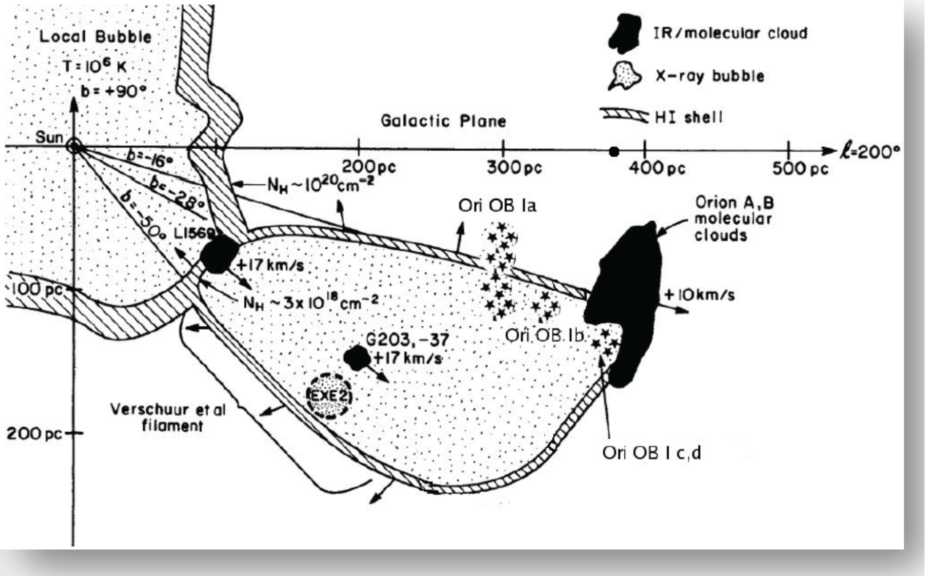


^{26}Al in Orion

- Now also detected with SPI/INTEGRAL

Siegert & Diehl (2016), arxiv 1609.08817

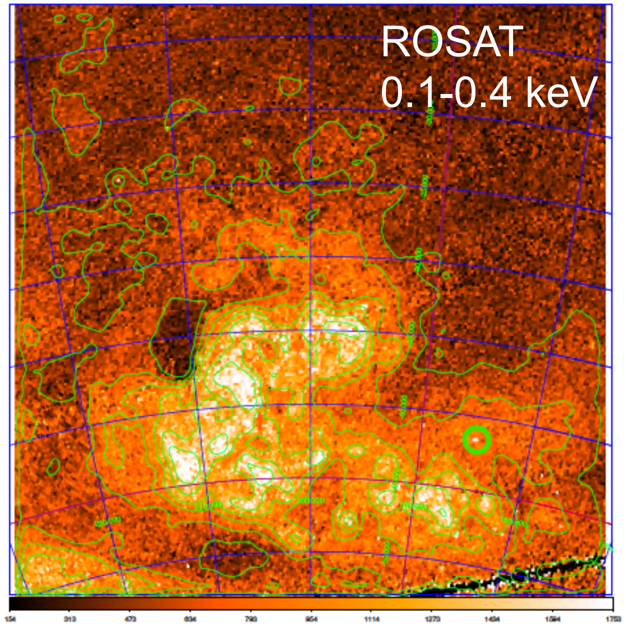


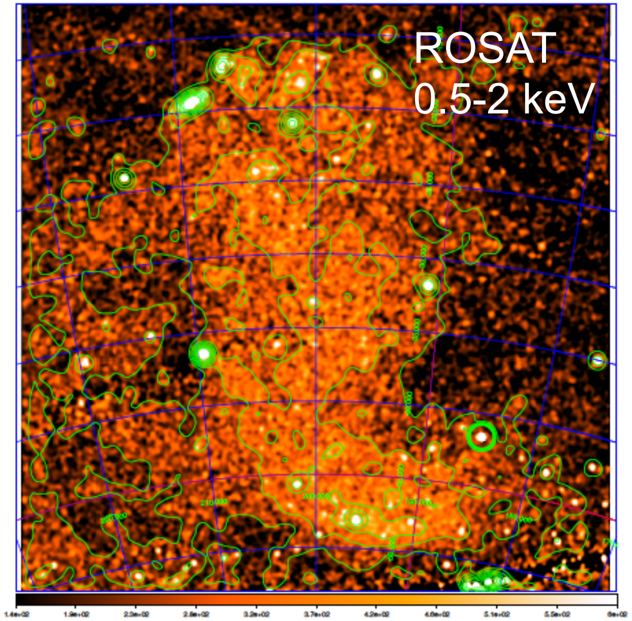


→ Ejecta kinematics?? ← blue shift; velocity broadening?

Understanding the Eridanus Superbubble

- X-ray Emission, size, ^{26}Al





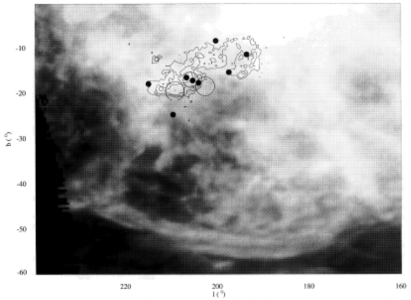
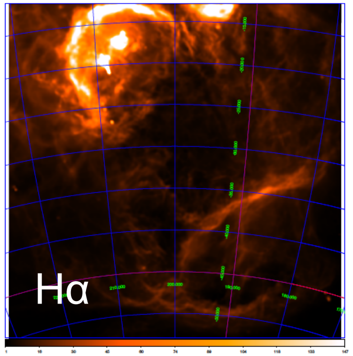
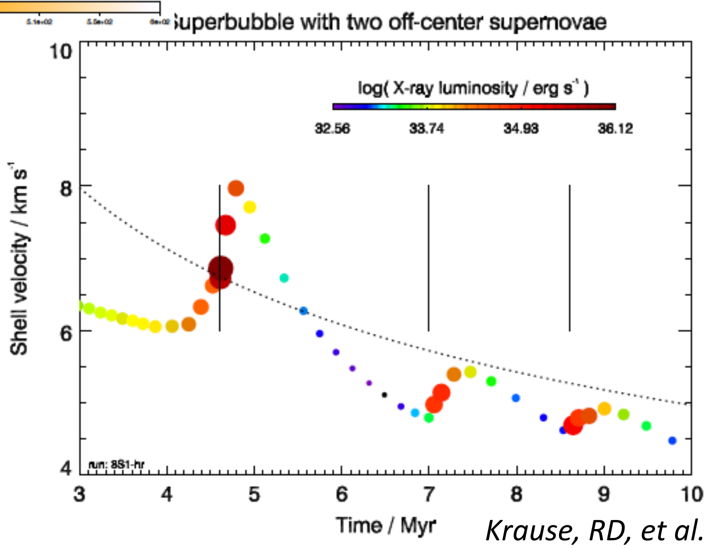


Fig. 7. The position of the Orion OB1 association with respect to the H I shell. The grey scale image is a logarithmically scaled representation of integrated H I emission in the velocity interval $-1\ \mathrm{km\,s^{-1}} \leq v_{\rm LSR} \leq +8\ \mathrm{km\,s^{-1}}$. The contours outline the 100 μm (IRAS) emmission from the Orion A and B molecular clouds (the ring around $(\ell, b) = (195°, -12°)$ is the λ-Orionis ring). The dots show the brightest stars in the Orion constellation. The circles show the positions of the three main subgroups of Orion OB1. From right to left are shown 1a, 1b and 1c



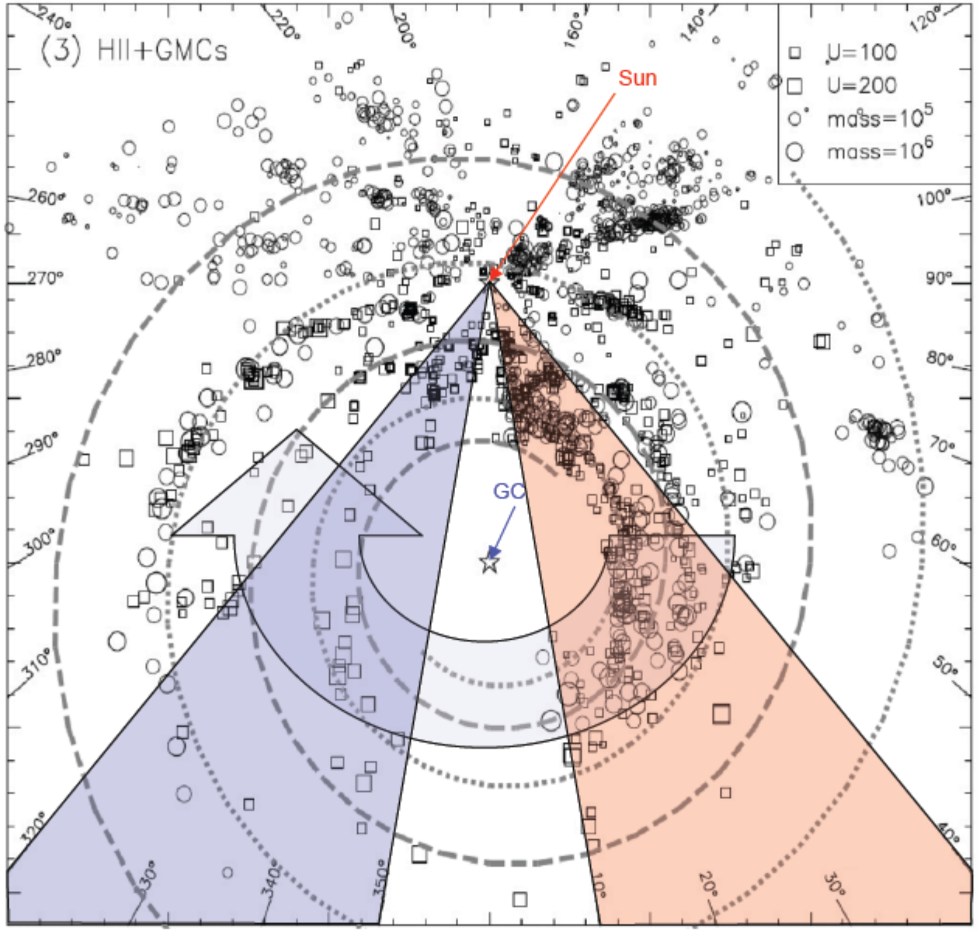
  - Temporal X-ray brightenings after SN energy injections
  - spatial oscillations

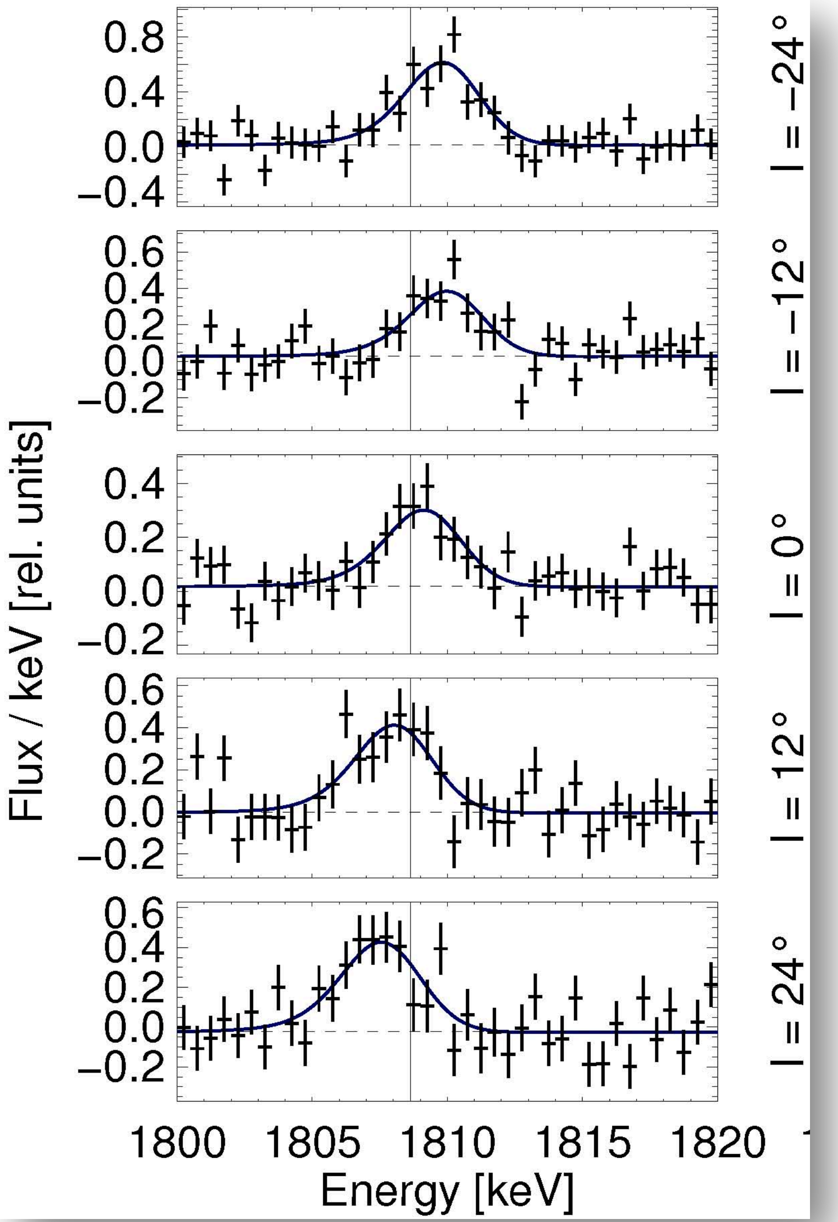


Krause, RD, et al. 2015

Views of SN ejecta in our Galaxy: ^{26}Al γ-rays

- Large-scale Galactic rotation

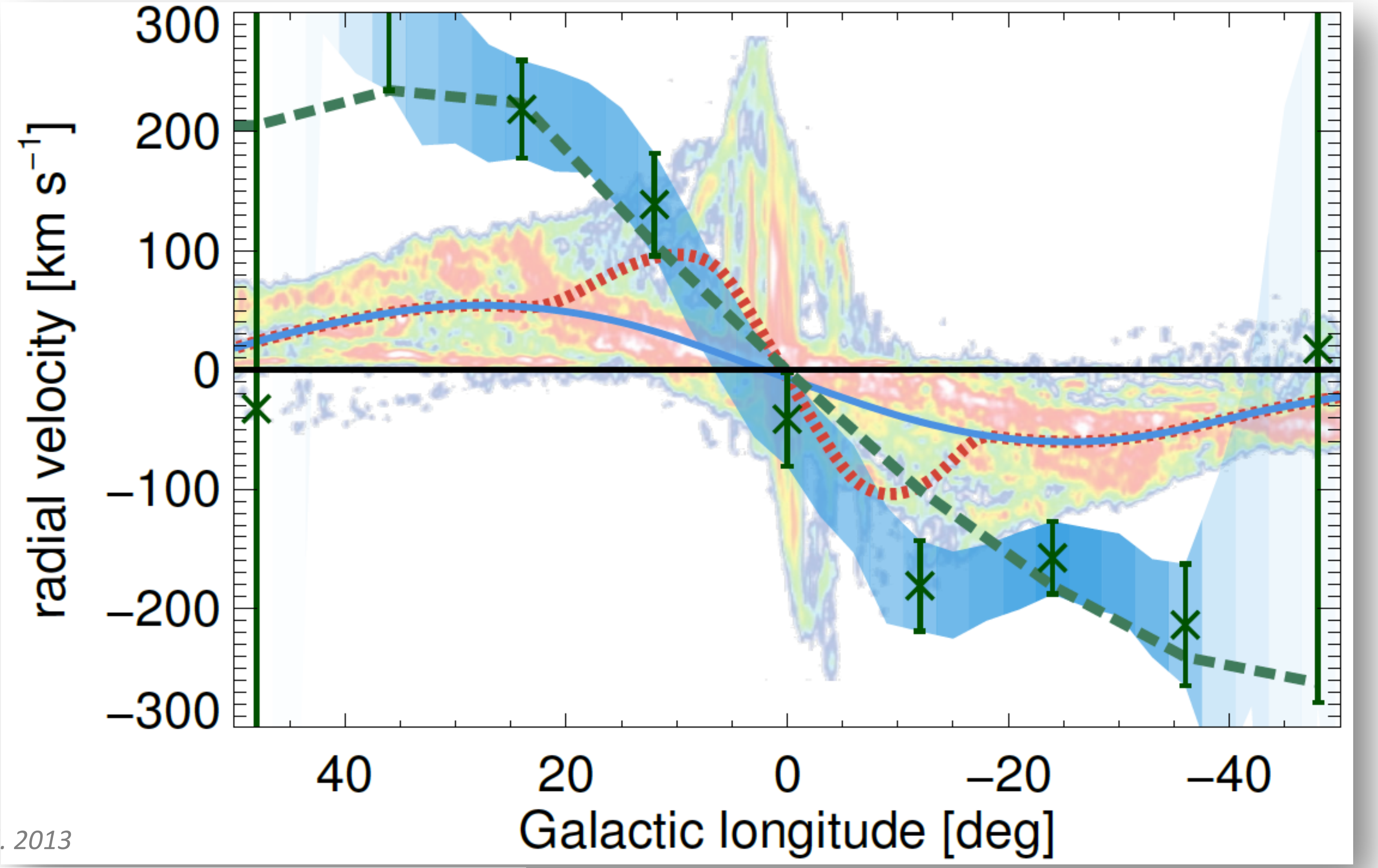




Kretschmer et al., A&A (2013)

The Galactic View: longitude-velocity diagrams

- excess velocity seen for massive-star ejecta!



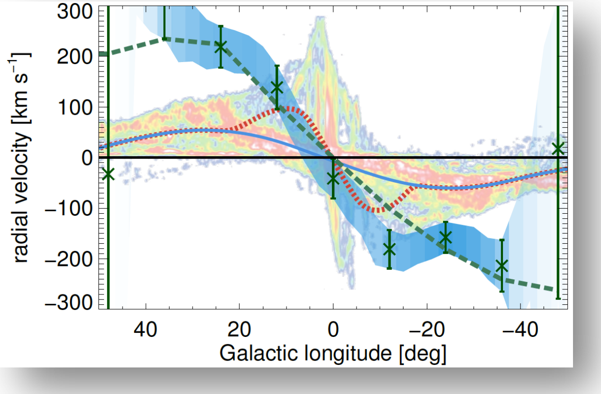
Kretschmer, Diehl, et al. 2013

Kinematics of massive star ejecta in the Milky Way as traced by ^{26}Al

Karsten Kretschmer[1,2], Roland Diehl[2,3], Martin Krause[2,3], Andreas Burkert[4,3,2],
Katharina Fierlinger[3,4], Ortwin Gerhard[2], Jochen Greiner[2,3], and Wei Wang[5]

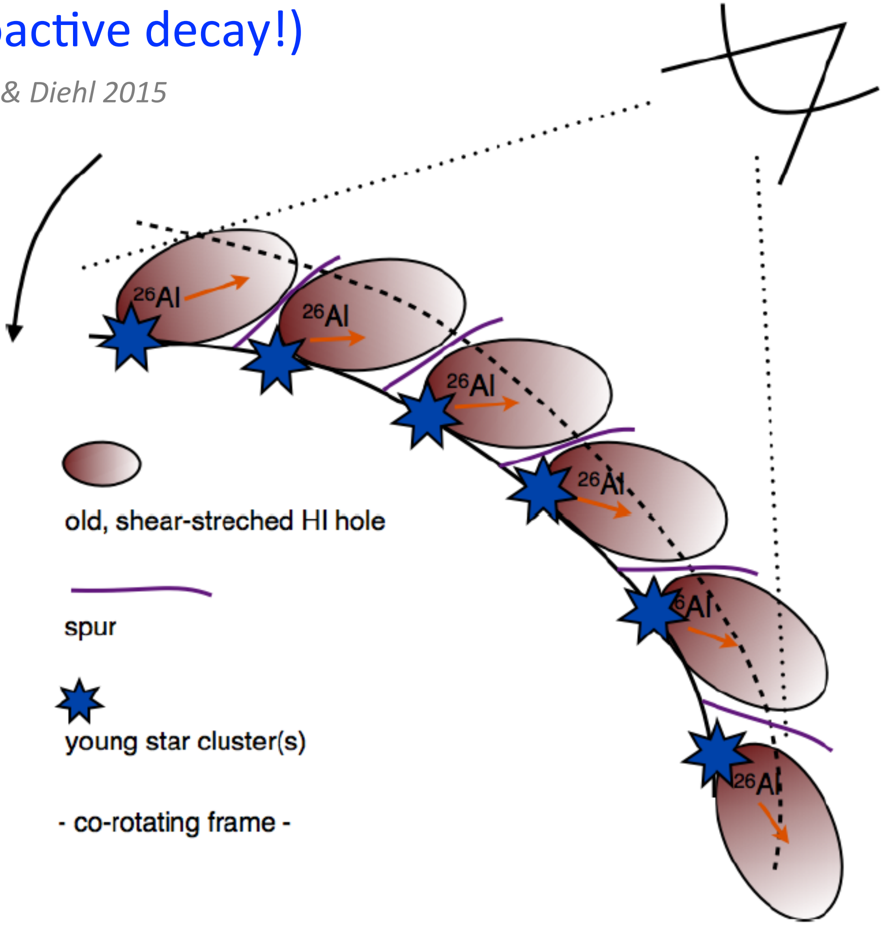
Superbubbles and HI Holes

- ^{26}Al ejecta flow into forward-extended (inter-arm) cavities → 200 km/s extra velocity



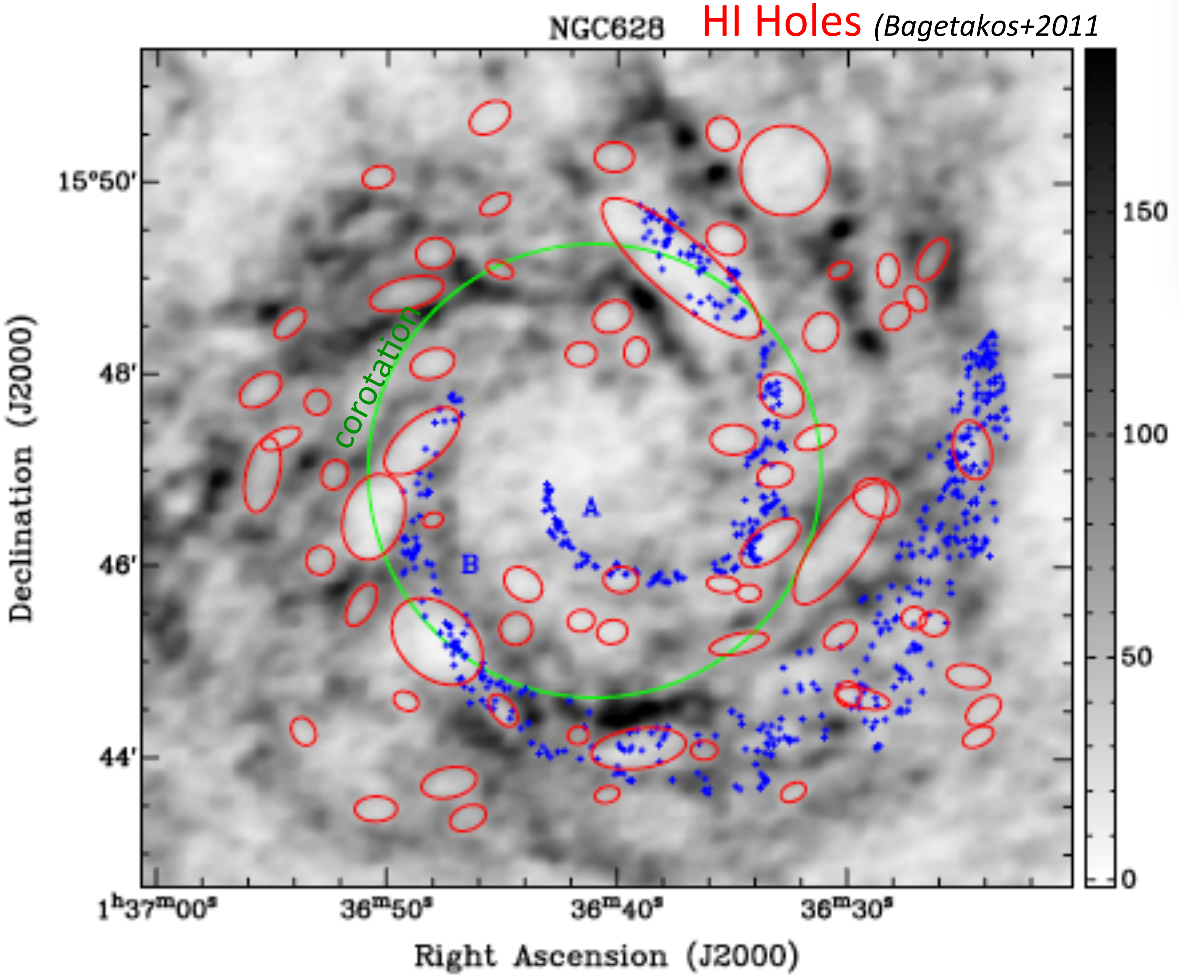
(radioactive decay!)

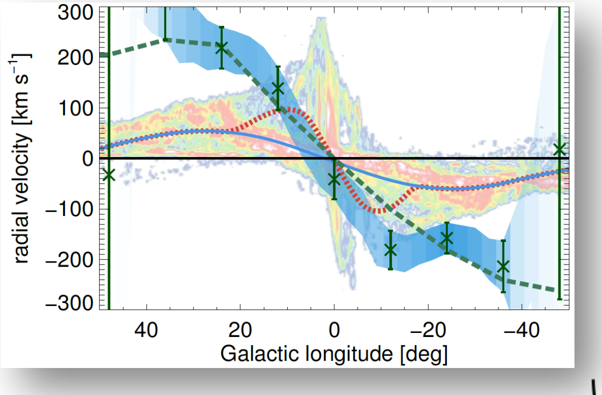
Krause & Diehl 2015

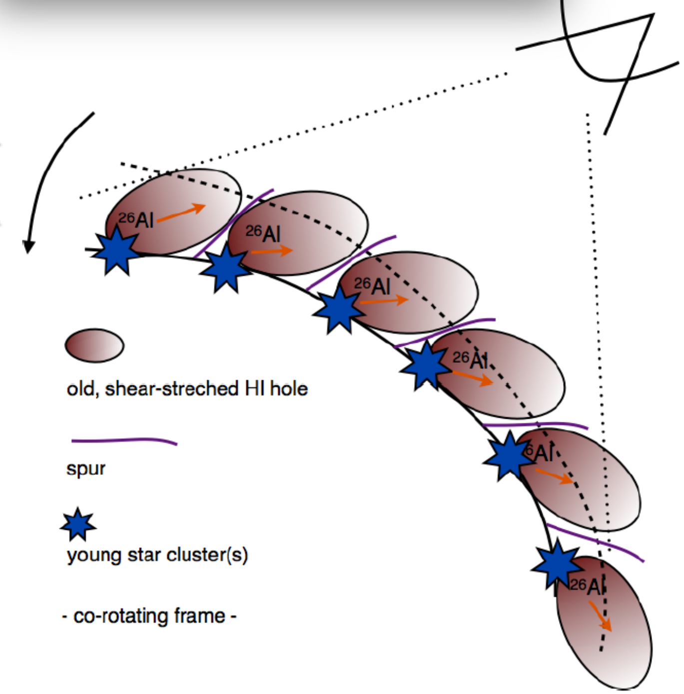


Superbubbles and HI Holes

- ^{26}Al (=SN-Ejecta) are predominantly streaming into large superbubbles

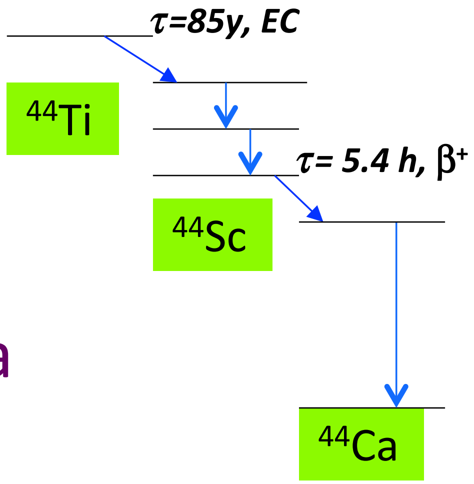

HI Holes *(Bagetakos+2011*





Summary SN Gamma-Rays

- ^{44}Ti γ-rays show kinematics of inner ccSN products
  - Doppler-broadened (multi-component?) Lines from ^{44}Sc and ^{44}Ca
  - Brighter ^{44}Ca line appearance
    → γ-rays from nuclear deexcitation??



- ^{56}Ni decay chain γ-rays shed new light on SNIa
  - ^{60}Co Lines at 847, 1238 keV emerge at >70 days and Doppler broadened ✔
  - Puzzling: early ^{56}Ni lines (He detonation?), irregular ^{56}Co line appearance

- Supernova Population Aspects:
  - ^{44}Ti-producing ccSNe are rare
  - SN explode mostly into superbubbles